and the solution which maintains the temperature

$$F(t) = \frac{t}{c^2+t^2}$$

for all time over $\rho = a$, is

$$v = 2k\int_0^\infty \lambda\,d\lambda \cos kc\lambda^2 \frac{J_0(\lambda\rho)}{J_0(\lambda a)} e^{-\lambda^2 kt}$$

$$+4k\int_0^\infty \frac{\lambda\,d\lambda\{J_0(\lambda\rho)\,Y_0(\lambda a) - Y_0(\lambda a)\,J_0(\lambda\rho)\}}{Y_0^2(\lambda a)+\pi^2 J^2(\lambda a)}\, e^{-\lambda^2 kt}\int_0^\infty \frac{x\cos kcx^2}{x^2-\lambda^2}\,dx$$

and these integrals can be much reduced.

Further illustrations, and further reduction of such a solution into other forms readily possible, do not seem necessary. Our object has been served by the indication of the general solution of problems involving a prescribed temperature variation over a cylinder.

This general solution can be made to apply to the internal space by using Orr's theorem between the limits zero and a. Any initial distribution which is not zero may be treated for both spaces by superposition.

A Study of Catalytic Actions at Solid Surfaces. Part VII.—*The Influence of Pressure on the Rate of Hydrogenation of Liquids in Presence of Nickel.*

By E. F. Armstrong, D.Sc., F.R.S., and T. P. Hilditch, D.Sc.

(Received October 3, 1921.)

In Parts I, II and V* of this series we have indicated the reasons which lead us to believe that during the catalytic hydrogenation of liquids the function of the metallic catalyst is to combine with both agents—the unsaturated organic compound and hydrogen—and produce an unstable intermediate complex. The experimental evidence has furthermore impressed upon us the conviction that the determining factor in hydrogenation is the degree of affinity displayed between nickel and the unsaturated compound; whilst we have had ample opportunity to observe the selective nature of the process as exemplified by the widely-varying rates of absorption of hydrogen characteristic of various definite types of organic compounds, we have not been fortunate enough to obtain experimental proof of the mode in which nickel effects the actual introduction of hydrogen to an organic molecule.

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* Part I, 'Roy. Soc. Proc.,' A, vol. 96, pp. 137–146 (1919); Part II, *ibid.*, A, vol. 96, pp. 322–329 (1919); Part V, *ibid.*, A, vol. 98, pp. 27–40 (1920).

We have, therefore, directed our attention to the influence of the concentration of hydrogen on the rate of hydrogenation of liquids, and have examined a wide range of unsaturated organic compounds with respect to the rates at which they absorb hydrogen under varying pressures. Existing data on this subject are scanty, but indicate, in the case of the hydrogenation of fatty oils, that the rate of action is simply proportional to the pressure.* On the other hand, it has been suggested† that the action of nickel is to adsorb the hydrogen (at the same time dissociating it into the atomic condition‡) and that it is the atomic hydrogen which interacts with the ethylenic linkage; if this were the case the acceleration induced by increasing the gas-pressure should be proportional to the square root of the latter.

The experiments now recorded were made in essentially the same apparatus as that described in Part I§ of this series; a small gas-compressor was however, inserted between the inlet gas meter and the hydrogenation vessel, the pressure being reduced again to atmospheric at the exit from the latter. In this way it was possible to obtain accurate continuous readings of hydrogen absorption, the actual gas-volumes being measured at atmospheric pressure.

The pressure in the system was allowed to reach the desired limit some moments before readings were commenced, the meters were then checked against each other, and readings taken at short intervals. Hydrogen absorption time curves were plotted in the ordinary way and the absorptions per minute under varying pressures over corresponding ranges of the absorption curves were then compared.

The results of the investigation were very definite and fall into three divisions:—

(i) *Normal.*—In the absence of substituent groups of the kind discussed below (iii) and in presence of sufficient nickel (in general so long as at least 0·1 per cent. of nickel is present), the ethylenic union is hydrogenated at a rate which is in almost exact proportion to the absolute pressure of the hydrogen.

(ii) *Subnormal.*—At very low concentrations of catalyst (*e.g.*, 0·01 to 0·02 per cent. of nickel reckoned on the organic compound) the increase in rate of hydrogenation becomes less than proportional to the increase in pressure. The compounds which absorb hydrogen most readily are in general more prone to show this subnormal effect when the catalyst concentration is diminished, and it is especially marked in the case of multi-ethylenic compounds such as derivatives of linoleic acid or linolenic acid, or citral.

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* Moore, Richter, and van Arsdel, 'J. Ind. Eng. Chem.,' vol. 9, p. 541 (1917); Maxted, 'J. Soc. Chem. Ind.,' vol. 40, pp. 169–171 T (1921).

† Thomas, 'J. Soc. Chem. Ind.,' vol. 39, pp. 120–124 T (1920); Lewis, 'J. Chem. Soc.,' vol. 117, pp. 623–638 (1920).

‡ Sieverts, 'Zeitsch. Physikal. Chem.,' vol. 77, pp. 591–613 (1911).

§ *Loc. cit.*, p. 138.

(iii) *Abnormal.*—If the unsaturated compound contains another group which has affinity towards nickel (but is not open to hydrogenation), we find that increase in hydrogen pressure causes an increase in the rate of hydrogen absorption in more than simple proportion to the altered concentration of hydrogen.

This has been observed with unsaturated alcohols and unsaturated carboxylic acids: the carboxyl group tends, of course, to act upon nickel producing the nickel salt of the acid and hydrogen, although at the higher temperatures of hydrogenation (180° C.) the equilibrium is moving in the direction of reduction of the salt by hydrogen to free acid and metallic nickel. The hydroxyl group in alcohols is also affected by nickel, although the latter is not, strictly speaking, an active catalyst of dehydration; thus, numerous instances have been recorded of side actions in the hydrogenation of the vapours of unsaturated alcohol over nickel in which formation of a hydrocarbon and water occur (*e.g.*, phenol at 180° C. yields cyclohexanol mixed with a little cyclohexanone and cyclohexene;* benzylalcohol gives toluene and methylcyclohexane;† geraniol yields some dimethyloctane as well as the saturated dimethyloctanol‡). On the other hand, unsaturated aldehydes and ketones have shown, in each case which we have examined, increases in rate of absorption of hydrogen in simple, or less than simple, proportion to the pressure, so that we may summarise the results as follows:—

Unsaturated compound.	Effect of pressure.
Alcohols $R{\cdot}CH{:}CH{\cdot}CH_2(OH)$.........	Abnormal.
Aldehydes (ketones) $R{\cdot}CH{:}CH{\cdot}CHO$	Normal (or subnormal).
Acids $R{\cdot}CH{:}CH{\cdot}COOH$	Abnormal.

This behaviour is in keeping with the generalisation outlined above, since the carbonyl residue CO is, in contrast to the hydroxyl and carboxyl groups, open to direct hydrogenation.

The results are broadly, then, that increase in concentration of hydrogen causes a directly proportionate increase in the rate of hydrogenation, providing there are no disturbing factors; and that the increase in rate of hydrogenation becomes abnormally large if other groups active towards nickel, but not open to hydrogenation, are also present. In other words, the nature of the unsaturated organic compound has a determining influence on the effect of the hydrogen concentration.

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* Sabatier and Senderens, 'Compt. Rend.,' vol. 137, p. 1025 (1903).

† Sabatier and Senderens, 'Bull. Soc. Chim.' [3], vol. 33, p. 616 (1905).

‡ Enklaar, 'Ber.,' vol. 41, p. 2085 (1908).

The above general results of our investigation may be illustrated by a few instances selected from the somewhat large number of compounds which we have investigated. The experimental data are given in the form of (i) the mean rates of absorption of hydrogen (litres per minute) over the same range of hydrogenation at varying pressures; and (ii) the ratios of these rates at the higher pressures to that at atmospheric pressure of hydrogen taken as unity. Observations were made at unit increments of pressure (atmospheres) from 1 to 4 or 5 atmospheres absolute.

I. NORMAL ACCELERATION WITH INCREASING PRESSURE (SIMPLE ETHYLENIC COMPOUNDS).

The data for ethyl cinnamate, ethyl linoleate and pinene may be taken as typical.

Ethyl Cinnamate.

As shown in Part V of this series of papers (*loc. cit.*), this ester is smoothly converted in the liquid state at 140° to 180° C. to ethyl β-phenylpropionate by passage of hydrogen in presence of nickel, the rate of absorption being practically constant for the greater part of the action.

176 grm. of pure ethyl cinnamate were hydrogenated at 140° C. in presence of 0·15 grm. of prepared nickel (0·085 per cent. Ni on the ester):—

Absolute pressures.	Mean rate of absorption.	Relative rates.
atm.	litres per minute.	
1	0·496	1·00
2	1·031	2·08
3	1·488	3·00
4	1·990	3·95

Ethyl Linoleate.

The ethyl linoleate employed was mixed with small proportions of ethyl oleate and ethyl esters of saturated fatty acids; these do not interfere with the course of hydrogenation which, as we have previously shown,* is selective and may be divided, so far as the rate of hydrogenation is concerned, into two phases: (i) an almost linear section of the absorption/time curve covering the action in which the esters less saturated than oleate are converted to a mixture of oleate and iso-oleates; and, after an abrupt fall in the rate of absorption, (ii) another sector of the curve corresponding to the production of stearate from the oleate and iso-oleates.

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* Part I, p. 142.

150 grm. of ethyl linoleate (previously distilled in a vacuum) were hydrogenated in presence of 0·45 grm. of nickel (0·3 per cent. Ni on the ester) at 180° C.

Absolute pressures.	Mean rates of absorption.	Relative rates.
atm.	litres per minute.	
	(i) Pre-oleate phase.	
1	0·8065	1·00
2	1·4495	1·80
3	2·2725	2·83
	(ii) Oleate phase.	
1	0·2293	1·00
2	0·4329	1·89
3	0·6665	2·91

Pinene.

The hydrogenation of pinene was studied to examine the behaviour of a simple ethylenic hydrocarbon in the liquid state; Sabatier and Senderens* have shown that it is converted smoothly into dihydropinene, the bridged-ring system remaining unaltered.

The hydrogenations were conducted at 160° C., at which temperature the vapour pressure of the pinene is approximately one atmosphere; consequently the effective pressure of hydrogen was one atmosphere less than the absolute pressure. The data obtained show that the acceleration in rate of hydrogenation was in simple proportion to the nett effective hydrogen pressure.

150 grm. of pinene were treated with hydrogen in presence of 0·30 grm. of nickel (0·2 per cent. Ni on the hydrocarbon) at 160° C. The absorption/time curve for pinene is of the approximately linear type.

Absolute pressures.	Partial pressure of hydrogen.	Mean rate of absorption.	Relative rates.
atm.		litres per minute.	
2	1	0·2595	1·00
3	2	0·5415	2·08
4	3	0·7956	3·05

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* 'Compt. Rend.,' vol. 132, p. 1256 (1901).

II. SUBNORMAL ACCELERATION WITH INCREASING PRESSURE (SIMPLE ETHYLENIC COMPOUNDS).

Ethyl Cinnamate.

176 grm. of the ester were hydrogenated at 140° C. in presence respectively of 0·015, 0·030, and 0·150 grm. of prepared nickel.

	Mean rates of absorption. Litres per minute.			Relative rates.		
Per cent. Ni in ester ...	0·008	0·017	0·085	0·008	0·017	0·085
Absolute pressures.						
1	0·048	0·115	0·496	1·00	1·00	1·00
2	0·063	0·222	1·031	1·32	1·93	2·08
3	0·065	0·260	1·488	1·35	2·26	3·00
4	0·069	0·294	1·990	1·43	2·53	3·95

Linseed Oil Glycerides.

The following data were obtained with the refined glycerides of linseed oil hydrogenated at 180° C., and show the effect of pressure with varying concentrations of nickel over the two characteristic phases:—

(i) Hydrogenation of linolenin and linolein to olein and iso-oleins.

(ii) Hydrogenation of olein and iso-oleins to stearin.

(i) Pre-olein phase.

	Mean rates of absorption. Litres per minute.			Relative rates.		
Per cent. Ni in oil......	0·050	0·075	0·150	0·050	0·075	0·150
Absolute pressures. (Atm.).						
1	0·259	0·321	0·517	1·00	1·00	1·00
2	0·338	0·497	0·968	1·30	1·55	1·87
3	0·450	0·595	1·500	1·74	1·85	2·90
4	0·540	0·773	2·112	2·09	2·41	4·09

(ii) Olein phase.

	Mean rates of absorption. Litres per minute.		Relative rates.	
Per cent. Ni in oil	0·075	0·150	0·075	0·150
Absolute pressures. (Atm.).				
1	0·096	0·108	1·00	1·00
2	0·162	0·236	1·69	2·18
3	0·230	0·317	2·40	2·94

III. ABNORMAL ACCELERATION WITH INCREASING PRESSURE (UNSATURATED ALCOHOLS AND ACIDS).

Geraniol.

Enklaar (*loc. cit.*) has shown that the products of vapour hydrogenation of geraniol are dimethyloctanol and dimethyloctane; we have found that, when this alcohol is hydrogenated in the liquid state, the formation of hydrocarbon only takes place to a very limited extent, and the action may be considered as practically normal.

100 grm. of geraniol were treated at 150° C. with hydrogen at varying pressure in presence of 0·50 grm. of prepared nickel.

Absolute pressure.	Mean rates of absorption.	Relative rates.
Atm.	litres per minute.	
1	0·127	1·00
3	0·521	4·10
4	0·720	5·67

Terpineol.

When hydrogenated over nickel in the state of vapour, terpineol yields exclusively the hydrocarbon hexahydrocymene, even at the low temperature of 125° C.;* but we have found that, operating with liquid terpineol at 150° C., direct addition of a molecule of hydrogen occurs with but little production of hydrocarbon, the action being thus more comparable with the reduction of liquid terpineol by means of palladium.†

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* Haller and Martine, 'Compt. Rend.,' vol. 140, p. 1303 (1905).

† Wallach, 'Annalen,' vol. 336, p. 37 (1904).

150 grm. of terpineol were hydrogenated at 150° C. in presence of 0·50 grm. nickel (0·33 per cent. Ni on the terpineol).

Absolute pressure.	Mean rates of absorption.	Relative rates.
Atm.	litres per minute.	
1	0·154	1·00
2	0·493	3·20
3	0·857	5·57
4	1·096	7·12
5	1·235	8·00

These results are characteristic for a number of unsaturated alcohols which we have studied, the relative rates being more abnormally high in the case of tertiary alcohols (terpineol and linaleol) than primary alcohols.

Oleic Acid.

200 grm. of highly refined oleic acid were hydrogenated at 180° C. in presence of 0·30 and 0·75 grm. of prepared nickel.

	Mean rates of absorption. Litres per minute.		Relative rates.	
Per cent. Ni in acid............	0·150	0·375	0·150	0·375
Absolute pressures. (Atm.).				
1	0·0471	0·2239	1·00	1·00
2	0·1332	0·5068	2·83	2·26
3	0·2300	0·8378	4·88	3·74
4	0·3073	1·1723	6·53	5·23

The abnormally high increases in rate of hydrogen absorption with increasing pressure may be contrasted with the direct proportionality of the figures for the olein phase of the hydrogenation of ethyl esters or glycerides of unsaturated fatty acids (pp. 244, 246); it is to be noted that the abnormality becomes somewhat less at relatively high concentrations of nickel.

IV. UNSATURATED ALDEHYDES AND KETONES.

These compounds are particularly interesting, in view of the results set out above, since, on the one hand, they contain an oxygenated group intermediate in constitution between the alcoholic and carboxylic radicles, and, on the other hand, this oxygenated group is, in contrast to the latter, one that will combine with hydrogen in presence of nickel. They are thus more comparable, from the point of view of hydrogenation, with a di- or multi-ethenoid compound than with a combination of ethylenic linkage and a free hydroxyl or carboxyl radicle.

The effect of pressure on the rate of hydrogenation is, as a matter of fact, closely similar to that which is encountered with such multi-ethylenic substances as linolein or linolenin—an increase in rate which is in direct proportion, or else somewhat less than proportional, to the pressure.

The abnormal increases in rate of hydrogenation with increase of pressure which characterise both unsaturated alcohols and carboxylic acids do not appear in the case of the unsaturated aldehydes or ketones. The hydrogenation of citral and of carvone may be cited as typical examples.

Citral.

Brochet* states that citral in the liquid state absorbs hydrogen readily in presence of nickel; we find that the addition of hydrogen is simple until saturation is approached, when side actions other than hydrogenation are apt to set in. The data now published therefore deal with the earlier part of the hydrogenation process, during which the simple hydrogenated citral is the only product of the action.

150 grm. of citral were hydrogenated at 150° C. in presence of 0·50 grm. nickel (0·33 per cent. Ni on the citral).

Absolute pressures.	Mean rate of absorption.	Relative rates.
Atm.	litres per minute.	
1	0·152	1·00
2	0·230	1·51
3	0·345	2·27
4	0·457	3·01

The relative increases in rate of hydrogenation are definitely subnormal, when compared with the speed of hydrogen absorption at atmospheric pressure; whilst the rates at 2, 3, and 4 atmospheres pressure, compared between themselves, are in the ratio 2·00 : 3·00 : 3·97, *i.e.*, in exactly direct proportion.

It is instructive to contrast these figures with the abnormally high ratios for the closely related alcohol geraniol (p. 246).

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* Brochet, 'Bull. Soc. Chim.' [4], vol. 13, p. 197 (1913).

Carvone.

Vavon* found that in presence of platinum black carvone can be hydrogenated successively to carvotanacetone, tetrahydrocarvone (carvomenthone) and tetrahydrocarveol. We have obtained the same sequence of changes employing nickel with liquid carvone at 150° C.; the final reduction to tetrahydrocarveol is more difficult than the other stages, and we have compared the rates of hydrogenation at varying pressures only in the case of the saturation of the two ethylenic linkages of the ketone.

The data are quoted for ranges of hydrogen absorption representing approximately the addition of the first and second molecules of hydrogen per molecule of carvone, and within these respective ranges the ratios remained closely constant, a change from normal to somewhat subnormal values occurring at that part of the absorption.

150 grm. of carvone were hydrogenated in presence of 0·50 grm. of nickel (0·33 per cent. Ni on the carvone).

Absolute pressures.	Mean rates of absorption.		Relative rates.	
	1st mol. H_2.	2nd mol. H_2.	1st mol. H_2.	2nd mol. H_2.
Atm.				
1	0·406	0·399	1·00	1·00
2	0·803	0·673	1·98	1·69
3	1·282	1·058	3·16	2·65

THEORETICAL CONCLUSIONS.

We have put forward the view† that the fundamental action in hydrogenation by nickel or other like catalyst is the balanced action

$$\text{(i) } Ni + \text{-}CH{:}CH\text{-} \underset{\longleftarrow}{\overset{\rightharpoonup}{=}} (Ni, \text{-}CH{:}CH\text{-}),$$

an extremely rapid equilibrium action, with the balance largely in favour of the unassociated components as indicated by the two arrows.

The slower action which is actually measured in work of this kind is, we consider, the interaction of this complex and hydrogen which is also associated with the nickel:—

$$\text{(ii) } (Ni, \text{-}CH{:}CH\text{-}) + H_2 \rightleftarrows (Ni, \text{-}CH{:}CH\text{-}, H_2) \rightleftarrows (Ni, \text{-}CH_2{\cdot}CH_2\text{-}) \rightleftarrows Ni + \text{-}CH_2{\cdot}CH_2\text{-}.$$

This view of the process of hydrogenation receives fresh support from the data on the relation between pressure and rate of hydrogenation which we now put forward; the bearing of the latter may be considered in connection with the three classes into which they fall:—

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* Vavon, 'Comp. Rend.,' vol. 153, p. 68 (1911).

† Part I, p. 144.

1. *Simple Ethylenic Compounds—Simple Proportionality between Concentration of Hydrogen and Rate of Hydrogenation.*

The direct proportionality observed in the case of simple unsaturated compounds (except for extremely low concentrations of catalyst) can only mean that the rate of addition of hydrogen is connected directly with the concentration of the hydrogen as it is presented in the system, *i.e.*, in the molecular form $-H_2$.

If the action were brought about by atomic hydrogen ($-H$) it would appear that one of two alternatives must occur:—

(*a*) The measured action might be that of the dissociation of hydrogen in presence of nickel (*cf.* Sieverts, *loc. cit.*),

$$H_2 \rightleftarrows 2H,$$

in which case the observed rate should vary as the square root of the hydrogen concentration and *moreover, should be independent of the constitution of the organic compound.*

(*b*) The measured action might be analogous to that given above (ii), and of the type:—

$$\text{-CH:CH-} + (\text{Ni}, 2\text{H}) \rightleftarrows (\text{-CH:CH-}, \text{Ni}, 2\text{H}) \rightleftarrows \text{Ni} + \text{-CH}_2\cdot\text{CH}_2\text{-}\cdot$$

The increase in rate should then be proportional to the square of the increase in pressure, and could only appear in the observed simple proportion if both actions (*a*) and (*b*) were of the same velocity, an extreme coincidence which again excludes any possibility of varying rates of hydrogenation conditioned by the type of unsaturated compound—the factor which is most prominent in all our results.

It follows that the general results of this enquiry indicate that the speed of hydrogenation is directly proportional to the molecular concentration of the hydrogen, as expressed in our general equation (ii) above.

2. *Simple Ethylenic Compounds—Very Low Concentrations of Catalyst.*

We have shown that in this case the increase in rate of hydrogenation is subnormal, *i.e.*, is in less than direct proportion to the increase in pressure.

Now, considering the initial action

$$\text{(i)}\ \text{Ni} + (\text{-CH:CH-}) \rightleftarrows (\text{Ni}, \text{-CH:CH-}),$$

it is evident that the relatively low concentration of nickel (and corresponding relatively high concentration of unsaturated compound) will tend to displace the equilibrium more in the direction of the complex (Ni, $-CH:CH$) so that more of the nickel present will be monopolised by association with the unsaturated compound and consequently the hydrogen will have less nickel available for the preliminary association of hydrogen and nickel. Hence increased concentration of hydrogen cannot produce its full normal effect, the hydrogen and unsaturated compound competing, as it were, for the attention of the small amount of nickel present.

It must be borne in mind that the amount of hydrogen brought into contact with nickel and the organic liquid at any one moment is very small and is not comparable with the amount of unsaturated compound except quite towards the end of the action. For example, the apparatus which we have employed (using about 1 gram-molecule of compounds such as ethyl cinnamate or terpene derivatives) contains about 500 c.c. free gas-space (at N.T.P.), so that if the whole apparatus were filled with a uniform mixture of solid nickel, liquid and gas (which will not occur in practice) the amount of hydrogen present at 0° would be only about 0·022 gram-molecules and at 150° to 180° C. only about 0·013 gram-molecules at atmospheric pressure.

3. *Unsaturated Compounds Containing Groups which have Affinity for Nickel but are not open to Direct Hydrogenation.*

The abnormally rapid increase with the pressure in the rate of hydrogenation of such compounds as unsaturated alcohols and acids is equally explained by the above mechanism; in this instance, in addition to the hydrogenation actions represented by (i) and (ii) we have a third, independent action between nickel and the additional group, so that the catalyst is occupied with three potential factors, unsaturated linking, hydrogen and the new radicle which is not capable of hydrogenation. Increase in concentration of the hydrogen will promote the action (ii) between ethylenic linking, nickel and hydrogen, but will have no direct influence on the association between nickel and the hydroxyl or carboxylic group. Consequently, and especially if the affinity between nickel and the other radicle is stronger than that between the metal and the unsaturated residue, the rate at which the action (ii) proceeds will increase abnormally with the pressure.

This behaviour may very possibly, also, be related to the general function of adsorption as defined by the work of Langmuir* and of Hardy.†

If, granting the presence of a suitable adsorbent surface, simple adsorption is conditioned by the relative affinities of various groups, the results which we have observed would follow when there is present at the surface (or forming the surface) a material which can induce actual chemical action between the less strongly attracted (adsorbed) of two or more radicles and an independently adsorbed substance (hydrogen).

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* 'J. Amer. Chem. Soc.,' vol. 38, p. 2221 (1916); vol. 39, p. 1848 (1917); vol. 40, p. 1361 (1918).

† 'Roy. Soc. Proc.,' A, vol. 86, p. 631 (1912); A, vol. 88, p. 303 (1913).

We have used the term adsorption here in the same sense as that in which Langmuir has defined it, namely, as a phenomenon which is caused by the same forces as are operative in any other chemical action; we regard "adsorption," if it is not absolutely identical with what we have referred to as "unstable intermediate compounds," as being the immediate precursor of the latter.

The investigation of the relation between hydrogen pressure and hydrogen absorption by unsaturated compounds in presence of nickel therefore has confirmed our former views of the primary dependence of the whole process upon the relations and affinities subsisting between the catalyst and the unsaturated organic compound.

On "Light Body" Hydrophones and the Directional Properties of Microphones.

By A. B. Wood, D.Sc., F.Inst.P., and F. B. Young, B.A., D.Sc., F.Inst.P.

(Communicated by Sir W. Bragg, F.R.S. Received March 10, 1921.)

The work to be described was carried out in August–September, 1916, and is now published with the permission of the Admiralty.

1. *Ellipsoidal Directional Hydrophones.*

Prof. W. H. Bragg in 1916 suggested a simple form of directional hydrophone, consisting of an elongated body of rigid but light construction, in which was mounted a carbon granule microphone of the "button" type. The principle of action of this body was expected to be as follows:—If a body floats freely, wholly or partly submerged, in water through which sound waves (or other waves) are passing, it oscillates with the water and with the same amplitude as the water, provided its dimensions are small compared with the wave-length. This follows from the fact that both the mass of the body and the forces which act on it are the same as in the case of the water which it has displaced.

If, however, the mass of the body is less than that of the water which it